

DIGITAL ACTUATOR CONTROL AND METHOD

TECHNICAL FIELD

[001] The invention relates to digital electromechanical controls in hard disk assemblies. More particularly, the invention relates to methods and apparatus for implementing control of an actuator with dynamic velocity compensation in disk drive systems.

BACKGROUND OF THE INVENTION

[002] The most common form of data storage for computers, hard disk drives in general share a similar basic head-disk assembly (HDA) structure. The actual disks, or platters, are traditionally made of a light alloy, glass or ceramic material coated with a very thin layer of magnetic medium. The magnetic layer has domains of magnetized areas oriented to store information through the use of read and write heads. Multiple platters on a disk drive are separated by disk spacers and are affixed to a rotatable spindle attached to a motor. The spindle is able to rotate all of the platters in unison. The motor is connected to a feedback loop to ensure the correct rotating speed, which may be on the order of 3,600 to 15,000 rpm.

[003] The read and write heads are typically attached to a single actuator arm that moves the heads around the platters as needed. When the platter is spinning, the heads ride on a cushion of air. When the platter is at rest, the heads come to rest, or park, at a predetermined landing zone or parking area. This parking area may include ramps used to move the heads off of the surface of the disk. In order to avoid damage to the disks, heads, and stored data,

precise control of the head actuator is critical in any head-disk assembly. Stepper motor actuators are known in the arts. Stepper motor actuators move the actuator over the platters in predefined steps. Stepper motor actuators are generally slow, blind to track position, incapable of meeting current track pitch requirements, prone to misalignment, and are sensitive to variations in temperature.

[004] In an attempt to address these problems, voice coil actuators, or servos, have been developed to control head movement. The voice coil is moved relative to a permanent magnet based on the magnitude of current flowing through it. Voice coil actuators get feedback as to position over the platter, assuring that the proper tracks are read, are not constricted to discrete steps, and are less sensitive to temperature changes. Voice coil actuators generally have small cables or springs designed to drag, with some reliance on windage, the heads into a park position when the drive is powered down. This approach is not desirable however, because it requires additional current to keep the heads on track over the middle of the disk. Additional problems arise in the control of the actuators. Frequent recalibration is necessary for servo motors to maintain precision. While tracking, position feedback from the disk surface is required. Distances between the parts of a disk drive, for example the heads and the platters, are extremely small. Therefore abrupt or imprecise movements of the actuator when parking or unparking can result in damage to the heads, data, or disks.

[005] Problems with imprecisely controlled movements in particular can arise due to the variability in the relative velocity and position of the actuator and

platter. Prior art actuator control has entailed providing a fixed current to the actuator motor. This approach has the disadvantage of causing the actuator motor to continuously accelerate for as long as the actuator motor current remains uninterrupted. Excessive acceleration of the actuator motor can cause damagingly abrupt actuator movements as in slamming into a fixed "crash stop" at an excessive velocity. An alternative prior art approach has been to provide a constant voltage across the actuator motor. This approach has the disadvantage of being unresponsive to changes in the load on the actuator motor. Load changes may occur during normal operation for a number of reasons, for example, when the heads are moved up a parking ramp, the load on the motor tends to increase. The increased load may cause the head to move more slowly, causing an overall loss of speed in the operation of the actuator arm. Efforts to avoid abrupt movements have traditionally relied on sampling the motor voltage using an analog circuit, and attempting to adjust the voltage applied to the actuator motor accordingly. The lack of flexibility and area requirements of the analog circuitry hamper the effectiveness of such efforts.

[006] Due to these and other problems with controlling the movement of actuators in HDAs, it would be useful and desirable in the arts to increase the speed and accuracy of monitoring for improved control. It would be particularly advantageous if improvements to actuator voltage control retract functions also contributed gains in terms of minimization of chip area and reductions in cost.

SUMMARY OF THE INVENTION

[007] In carrying out the principles of the present invention, in accordance with preferred embodiments thereof, methods for use in controlling an actuator in a

hard drive assembly are disclosed. Exemplary embodiments of the methods include steps of sampling the actuator voltage and processing an actuator voltage sample. From the results of the processing step, a digital voltage command is generated for controlling the application of voltage across the actuator.

[008] According to preferred embodiments of the invention, the sampling includes steps for the conversion of an analog actuator voltage to a representation in the digital domain for digital processing.

[009] According to further aspects of the invention, methods are disclosed in which the actuator is placed in a high impedance state for the sampling step.

[010] According to yet another aspect of the invention, a method of controlling an actuator includes waiting for a selected time interval and reiterating the sampling and processing steps.

[011] According to another aspect of the invention, the back-electromagnetic field (BEMF) of the actuator is calculated rather than measured, using the sampled actuator voltage and sampled actuator current. Additional steps include calculating a velocity error using the BEMF and a selected target voltage, producing a digital voltage command for compensating the actuator voltage for the velocity error, and applying a voltage at the actuator accordingly.

[012] According to another aspect of the invention, actuator apparatus of the invention is disclosed in which a sampler is provided for sampling actuator motor

voltage and outputting a digital actuator motor voltage sample. A timer is also provided for periodically activating the sampler. A digital processing engine is used to perform the bulk of the required processing for receiving a target actuator voltage command and the digital actuator motor voltage sample, and for outputting a digital voltage command for controlling the actuator voltage.

[013] The invention provides technical advantages including but not limited to increased precision and accuracy in actuator movement control functions using digital methods and circuitry. The digital approach of the invention provides a higher degree of flexibility in choosing the exact method of control, e.g. for faster sample rates accommodating higher bandwidth control. These and other features, advantages, and benefits of the present invention will become apparent to one of ordinary skill in the arts upon careful consideration of the detailed description of representative embodiments of the invention in connection with the accompanying drawings and tables.

BRIEF DESCRIPTION OF THE DRAWINGS

[014] The present invention will be more clearly understood from consideration of the following detailed description and drawings in which:

[015] Figure 1 is a block diagram illustrating an exemplary embodiment of a circuit and method of the invention;

[016] Figure 2 is a process flow diagram showing an example of a preferred embodiment of a method of the invention;

[017] Figure 3 is a process flow diagram illustrating an alternative embodiment of a method of the invention; and

[018] Figure 4 is a schematic block diagram showing an alternative representative embodiment of a circuit according to the invention.

[019] References in the detailed description correspond to like references in the figures unless otherwise noted. Like numerals refer to like parts throughout the various figures. Descriptive and directional terms used in the written description such as first, second, upper, lower, left, right, etc., refer to the drawings themselves as laid out on the paper and not to physical limitations of the invention unless specifically noted. The drawings are not to scale, and some features of embodiments shown and discussed are simplified or exaggerated for illustrating the principles, features, and advantages of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[020] In general, the invention samples the actuator voltage to dynamically determine the actuator velocity. The compensation needed in order to adjust the voltage across the actuator for improved actuator control is output, and the correct voltage is applied.

[021] First referring primarily to Figure 1, a schematic block diagram illustrates an example of a preferred embodiment of apparatus implementing the invention. In the circuit 10 shown, the actuator voltage V_{mtr} is sensed at the actuator motor 12. A digital processing engine 14 is electrically connected to process the actuator voltage V_{mtr} and a desired target actuator voltage V_{tgt} 16 as further

described. The sensed actuator voltage V_{mtr} is typically sampled using a sampler 18, in this case shown connected to an analog-to-digital converter 20. The A/D converter 20 facilitates digital sampling of the analog actuator voltage V_{mtr} in order to permit the digital processing engine 14 to be used to provide more rapid and accurate processing than would be possible with an analog device. A timer 22 is typically used to control the sampling and output functions, the latter preferably employing a digital-to-analog converter 24 in order to provide an analog output.

[022] The operation of the apparatus shown and described will be better understood with reference to the process flow diagram of Figure 2 illustrating an example of a preferred method of the invention. Figure 2 is also accompanied by Table 1, showing an alternative representation of steps of the exemplary method of the invention. Indicated in step 30, in preparation for sampling, the output voltage of the actuator V_{mtr} is disabled, placing the actuator motor in a high impedance state. A pause ensues in order to allow the residual current in the circuit to diminish to approximately zero, shown by step 32. The time duration of the pause is preferably pre-selected based on known electrical characteristics of the actuator. As shown in step 34, the voltage across the actuator V_{mtr} is sampled. This sampling provides an actual measurement of the electromagnetic field at the motor, also referred to as the back electromagnetic field, or BEMF. Now referring to step 36, the velocity error E_v is now calculated, preferably by subtracting the measured actuator voltage V_{mtr} from the target voltage V_{tgt} .

$$E_v = V_{tgt} - V_{mtr} \quad [\text{Equation 1}].$$

The voltage required to compensate for the velocity error E_v is then calculated, step 38. At step 40, an actuator voltage may now be applied to the actuator, providing compensation for any velocity error. The feedback loop of the circuit facilitates ongoing adjustments to the actuator voltage. At step 42, a pre-selected time interval is preferably allowed to elapse before the foregoing steps are repeated as indicated by the arrow path shown with step 44.

[023] The method steps depicted in Figure 2 are related in Table 1 in a high-level computer format. The sample code of Table 1 is representative of a preferred embodiment of the invention and it should be appreciated by those skilled in the arts that various alternative computer code and computer platforms may be used within the scope of the invention.

Table 1

set(hiz_1)	#1 - disable the output - put into high impedance state
wait(255)	#2 - wait for residual current to die out
wait(145)	
set(sel_1)	#3 - selects vmtr through adcmux
set(cnv_1,sel_1)	#initiate adc conversion of vmtr
hold	#wait for adc conversion to be complete
set(cnv_0)	
sto(vmtr)	#store the results of the adc conversion into memory
lac(target)	#4 - calculate velocity error = target - vmtr
sub(vmtr)	
sac(error)	#store results of error calculation

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add(errorold) #5 - apply compensation to the error
mpy(ki) #compensation is vcmd=ki*[x(n)+x(n-1)] + yi(n-1) #+kp*x(n) + ffwd
add(intold)
sac(intold)
lac(error)
sac(errorold)
mpy(kp)
add(intold)
add(ffwd)          #this is compensated error or the new vcmd
outac              #6 - apply voltage to the actuator
set(hiz_0)
wait(255)          #7 - leave drive voltage applied for a fixed amount of time
wait(255)
wait(90)
b(1)              #8 - repeat the process

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[024] An alternative preferred embodiment of a method of actuator control according to the invention is described with reference to the process flow diagram of Figure 3. Figure 3 is also accompanied by the example of Table 2. In this alternative embodiment, the steps resulting in the measurement of the actual motor voltage V_{mtr} are replaced with steps for calculating the BEMF without interrupting the actuator voltage. The voltage across the actuator motor V_{mtr} is sampled as shown at step 50. The current through the actuator motor I_{mtr} is also sampled, indicated at step 52. In step 54, the BEMF is calculated using the voltage and current samples according to,

$$BEMF = V_{mtr} - I_{mtr} * R_{mtr} \quad [\text{Equation 2}],$$

where R_{mtr} represents the resistance of the actuator motor. In order to compensate for variations in motor resistance, R_{mtr} is preferably calculated by initially providing a fixed current to the actuator so that it comes to rest against a crash stop. This ensures that the initial BEMF is zero. The motor resistance R_{mtr} is calculated by measuring the motor voltage V_{mtr} , and using Ohm's law, dividing by the motor current I_{mtr} . In step 56, this result is used to calculate the velocity error E_v , by subtracting the BEMF from the target voltage, V_{tgt} ,

$$E_v = V_{tgt} - \text{BEMF} \quad [\text{Equation 3}].$$

Knowledge of the velocity error E_v provides the ability to apply a compensating voltage, preferably as part of a digital voltage command V_{cmd} , as indicated at step 58, where $ffwd$ is the error compensation voltage,

$$V_{cmd} = k_i * [x(n) + x(n-1)] + y_i(n-1) + k_p * x(n) + ffwd \quad [\text{Equation 4}].$$

The updated voltage is then applied according to the digital voltage command at the actuator, step 60. The foregoing steps may be used to correct for velocity error in an actuator apparatus. Preferably, after delaying for a pre-selected time interval, step 60, the steps may be reiterated, as indicated by the arrow path from step 62. This technique provides dynamic actuator control with precise compensation for velocity error.

[025] The steps of the invention shown and described with reference to Figure 3 may be further understood by referring to the alternative representation of the invention shown in Table 2. The table is intended to be illustrative of high-level computer instructions for the implementation of an exemplary embodiment of the invention. It will be apparent to those skilled in the arts that various

alternative computer code and computer platforms may be used without departure from the scope of the invention.

Table 2

set(sel_1)	#1 - selects vmtr through adcmux
set(cnv_1,sel_1)	#initiate adc conversion of vmtr
hold	#wait for adc conversion to be complete
set(cnv_0)	
sto(vmtr)	#store the results of the adc conversion into memory
set(sel_0)	#2 – selects imtr through adcmux
set(cnv_1,sel_0)	#initiate adc conversion of vmtr
hold	#wait for adc conversion to be complete
set(cnv_0)	
sto(imtr)	#store the results of the adc conversion into memory
lac(imtr)	#3 – calculate bemf voltage = $vmtr - imtr * rmtr$
mpy(rmtr)	
sac(imtr)	
lac(vmtr)	
sub(imtr)	
sac(bemf)	
lac(target)	#4 - calculate velocity error = target - bemf
sub(bemf)	
sac(error)	#store results of error calculation
add(errorold)	#5 - apply compensation to the error
mpy(ki)	#compensation is $vcmd = ki * [x(n) + x(n-1)] + yi(n-1) + kp * x(n) + ffwd$
add(intold)	
sac(intold)	

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lac(error)
sac(errorold)
mpy(kp)
add(intold)
add(ffwd)          #this is compensated error or the new vcmd
outac              #6 - apply voltage to the actuator
wait(100)          #7 - leave drive voltage applied for a fixed amount of time
b(1)               #8 - repeat the process

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[026] An additional schematic view of a preferred embodiment of the invention is provided in Figure 4. An example of details of the digital processing engine 14 and associated circuitry 10 is shown. As directed by encoded instructions, for example Table 1 and Table 2, the circuit 10 samples the voltage across the motor, calculates the error, and determines the appropriate voltage command. Table 3 shows an alternative representation of how each of the commands of Tables 1 and 2 may be executed as shown in Figure 4. Mux_2 provides the ability to sample the voltage across the coil VCMP (12) or the current through the coil VISO to be sampled at the A/D converter adc_8 (20). Memory device mem_16x8 provides storage space for the variables used to calculate the compensated voltage command for transmission to a D/A converter dac_8. A math processing unit mpu_8 is used for performing mathematical functions and comparisons. The processing engine proper (also represented by numeral 14 in Figure 1) is indicated by udsp_a. It processes the commands indicated by Tables 1 and 2 and sets the appropriate control lines so that the appropriate execution may be achieved.

Table 3

Instruction Set

OPC	Instruction	Operand
0	null	8 bit null
1	lac	4 bit address 4 bit null
2	laci	8 bit data
3	sac	4 bit address 4 bit null
4	sto	4 bit address 4 bit null
5	set	8 bit mask
6	wait	8 bit data
7	hold	8 bit null
8	cmp	4 bit address 4 bit null
9	bgt	8 bit data (address?)
10	b	8 bit data (address?)
11	add	4 bit address 4 bit null
12	sub	4 bit address 4 bit null
13	mpy	4 bit address 4 bit null
14	div	4 bit address 4 bit null
15	null	8 bit null

Instruction Execution:

0 **null** 0000xxxxxxxx (1 cycle)

1. increment program counter

1 **lac** 0001xxxxaaaa (1 cycle)

1. set address lines A<3:0> to aaaa
2. set memory CS=1
3. set RD_WRZ=1
4. set mpu CMD=110
5. increment program counter

2 **laci** 0010dddddddd (1 cycle)

1. set data lines D<7:0> to ddddddd
2. set mpu CMD=110
3. increment program counter

3 **sac** 0011xxxxaaaa (2 cycles)

first cycle

1. set address lines A<3:0> to aaaa
2. set mpuoe=1
3. set memory CS=1
4. set RD_WRZ=0
5. set mpu CMD=111

second cycle

1. set address lines A<3:0> to aaaa
2. set mpuoe=1
3. set memory CS=0
4. set RD_WRZ=0

5. set mpu CMD=111
6. increment program counter

4 **sto** 0100xxxxaaaa (2 cycles)

first cycle

1. set address lines A<3:0> to aaaa
2. set memory CS=1
3. set adcoe=1
4. set RD_WRZ=0

second cycle

1. set address lines A<3:0> to aaaa
2. set memory CS=0
3. set adcoe=1
4. set RD_WRZ=0
5. increment program counter

5 **set** 0101mmmmmmmm (1 cycle)

1. set discrete outputs = mmmmmmmm
2. increment program counter

6 **wait** 0110ddddddd (n +1 cycles)

first cycle

1. set data lines D<7:0> to dddddddd
2. set mpu CMD=110

second through n cycles (repeat until eq is set)

1. set data lines D<7:0> to 00000001
2. set mpu CMD=001

n+1 cycle

1. increment program counter

7 **hold** 0111xxxxxxxx (? cycles)

first through ? cycles (repeat until in1 is set)

1. idle

last cycle

1. increment program counter

8 **cmp** 1000xxxxaaaa (1 cycle)

1. set address lines A<3:0> to aaaa
2. set memory CS=1
3. set RD_WRZ=1
4. set mpu CMD=100
5. increment program counter

9 **bgt** 1001dddddddd (1 cycle)

if gt=1

1. set program counter equal to dddddddd

else

1. increment program counter

10 **b** 1010dddddddd (1 cycle)

1. set program counter equal to dddddddd

11 **add** 1011xxxxaaaa (1 cycle)

1. set address lines A<3:0> to aaaa

2. set memory CS=1

3. set RD_WRZ=1

4. set mpu CMD=000

5. increment program counter

12 **sub** 1100xxxxaaaa (1 cycle)

1. set address lines A<3:0> to aaaa

2. set memory CS=1

3. set RD_WRZ=1

4. set mpu CMD=001

5. increment program counter

13 **mpy** 1101xxxxaaaa (n cycles?)

1. set address lines A<3:0> to aaaa
2. set memory CS=1
3. set RD_WRZ=1
4. set mpu CMD=010
5. increment program counter

14 **div** 1110xxxxaaaa (n cycles?)

1. set address lines A<3:0> to aaaa
2. set memory CS=1
3. set RD_WRZ=1
4. set mpu CMD=011
5. increment program counter

15 **outac** 1111xxxxxxxx (2 cycles)

first cycle

1. set mpuoe=1
2. set daclatch=1

second cycle

1. set daclatch=0

2. set mpuae=0

[027] A brief description of addition, from step 11, Table 3, is provided to show a representative example of the execution of a simple instruction. The instruction set is begun with:

11 **add** 1011xxxxaaaa (1 cycle).

- | | |
|-------------------------------------|---|
| 1. set address lines A<3:0> to aaaa | Sets the addresses for mem_16x8 |
| 2. set memory CS=1 | The memory block mem_16x8 is selected so that it may act as either an input or output device as further directed by RD_WRZ |
| 3. set RD_WRZ=1. | The memory mem_16x8 is configured so that the data stored at address "aaaa" is available at the D<7:0> bus |
| 4. set mpu CMD=000. | The mpu_8 is caused to add the value at D<7:0> to the value currently stored in its internal accumulator: |
| 5. increment program counter. | The program counter is then incremented so that the next instruction may be executed. The result of the present instruction is allowed to remain in the accumulator of mpu_8: |

[028] An example of MPU commands useful in understanding the preferred embodiment of the invention shown and described appears in Table 4. It should be understood that the examples shown and described are preferred embodiments and are intended to convey the concept of the invention and are not the sole possible embodiment of the invention.

Table 4

MPU COMMANDS

CMD	Operation	Action
000	add	acc=acc+in
001	subtract	acc=acc-in
010	multiply	acc=acc*in
011	divide	acc=acc/in
101	tbd	
102	lac	acc=in
103	sac	acc is available at mpu output.

[029] Thus, the invention provides methods, systems, and circuits for improved HDA actuator control responsive to digitally monitored actuator motor velocity. While the invention has been described with reference to certain illustrative embodiments, the description of the methods and devices described are not intended to be construed in a limiting sense. For example, many alternative digital processing engines may be used without departure from the invention.

Various modifications and combinations of the illustrative embodiments as well as other advantages and embodiments of the invention will be apparent to persons skilled in the art upon reference to the description and claims.